Initial testing of advanced ground-penetrating radar technology for the inspection of bridge decks – The HERMES and PERES Bridge Inspectors

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ABSTRACT

Since early 1995 the Federal Highway Administration (FHWA) has been sponsoring the development of ground-penetrating radar (GPR) technology to produce a tool for the non-destructive evaluation of bridge decks. Under contract with the FHWA, Lawrence Livermore National Laboratory (LLNL) designed and built a system capable of recording data over a 2 meter width during normal traffic flow. The derived system is called 'The HERMES Bridge Inspector' (High-speed Electromagnetic Roadway Measurement and Evaluation System) and includes a 64 channel antenna array within a 30 ft trailer. For detailed investigation of portions of a bridge deck, a robotic cart mounted radar has been developed. This cart system is named 'The PERES Bridge Inspector' (Precision Electromagnetic Roadway Evaluation System). PERES records data over the chosen area by rastering a single transceiver over the road. Images of the deck interior are reconstructed from the original synthetic aperture data using diffraction tomography. The work presented herein describes the findings of initial experiments conducted to determine the inspection capabilities of these systems. Internal defects such as delaminations, voids and disbonds; and construction details including deck thickness, asphalt overlay thickness and reinforcement layout were the features targeted. The final goal is for these systems, and other non-destructive technologies, to provide information on the condition of the nation's bridges for input to bridge management systems.

Keywords: bridge deck, bridge inspection, ground-penetrating radar, synthetic aperture, diffraction tomography.

1. INTRODUCTION

The bridge inventory within the United States, and worldwide, is aging and having to cope with increasing traffic volume. The deterioration of bridge structures is cause for concern and quantitative inspection methods are greatly needed. In particular, engineers desire some forewarning before the degradation becomes visible and the condition of the structure becomes critical. Early detection of internal defects allows direction of funds to the bridges at most risk. The availability of a rapid inspection capability that could be used to assess the bridge inventory would allow informed bridge management decisions to be made. This problem calls for non-destructive inspection techniques. To address this need the Federal Highway Administration (FHWA) is pursing a program of research and development of non-destructive evaluation methods.[1]

Of the major bridge components, the deck is the most subject to wear and exposure to the elements and is therefore one of the components most in need of inspection for deterioration. A deck inspection tool that may be used on reinforced concrete decks, including those with an asphalt overlay is required. Additionally, the derived inspection method should be feasible during the course of normal traffic flow without the need for lane closures. The FHWA has developed the 'HERMES Bridge Inspector' (High-speed Electromagnetic Roadway Measurement and Evaluation System) which uses advanced ground-penetrating radar (GPR) technology pioneered by Lawrence Livermore National Laboratory (LLNL). HERMES consists of an array of 64 horn antenna transceivers, controlling electronics, encoder wheel, computer workstation and data storage device all mounted inside a 30 ft towable trailer. A prototype precursor of HERMES was a robotic cart mounted GPR transceiver. This initial device has also been developed for use as a deck inspection system with applications where detailed inspection is required and lane closures allowed. The robotic cart system has been given the name of 'The PERES Bridge

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Inspector' (Precision Electromagnetic Roadway Evaluation System). Further description of HERMES and PERES may be found in past published conference proceedings.[2,3]

This paper highlights results of ongoing tests designed to evaluate the performance of the two systems. Field tests with HERMES and laboratory trials with PERES are reported.

2. PRIMARY SYSTEM TESTS

An initial test of the HERMES and PERES Bridge Inspectors was carried out during the summer of 1997 near Weaverville, CA.[4] Following this initial test, development of the systems was continued by Lawrence Livermore National Laboratory (LLNL) and a second field trial was conducted near Truckee, CA during July 1998. These tests were set up to verify the operation of HERMES before delivery to FHWA. Both systems have now been received by the FHWA at the Turner-Fairbank Highway Research Center (TFHRC), McLean, VA and performance testing has commenced.

Testing of HERMES and PERES is being conducted to establish that the systems operate satisfactorily as deck inspection tools. Both HERMES and PERES have been used in field tests. The results of HERMES testing in the field and PERES tests over deck slabs specially constructed with internal defects are presented.

2.1 HERMES testing methodology

HERMES combines data from 64 different channels into one datafile requiring the data from each channel to be de-multiplexed. To produce a single image, the data must be aligned to account for the individual antenna position in the array. To verify that this alignment process was functioning correctly, data were recorded over metallic tapes laid out on the surface of the test roadway. The tapes were marked out in the shape of an 'X' which should be visible in the processed data to indicate successful treatment of the data. To form an image of the interior of the deck, the aligned data is input to an inverse-modeling program. Multi-frequency diffraction tomography[5] is the technique used to produce the image. The resulting images are referred to as 'reconstructions', as the processing technique attempts to reconstruct the structure which caused the measured data.

The volume of data collected with HERMES depends on the number of recorded samples per waveform, the sample spacing along the road, and the number of transceivers fired over the array. With 64 transceivers and a sampling rate of 256 samples per waveform, 34 KB of data is acquired at every measurement position of the array. Accordingly, for 3 cm spacing in the direction of travel, 1.2 MB of data is generated. To accommodate all the files associated with processing the data however, the amount of space has to be increased by a factor of 4.1. Once the data has been de-multiplexed and aligned, only the last datafile is required and the original, or raw data, and the de-multiplexed data may be discarded.

At present, HERMES has been tested on four bridges which were scheduled for repair. HERMES is shown in Figure 1 at the test bridge near Truckee, CA.

Figure 1. Field testing with HERMES.

At the Truckee tests, the HERMES trailer was towed across the bridge deck and data collected during a series of different passes. These separate passes were designed to investigate how system setup parameters including travel speeds, height of array above road surface, and spacing of measurements affected the quality of data.

2.2 PERES testing methodology

The initial tests of PERES have focussed on data collection over slabs fabricated with simulated defects. The laboratory specimens represent simpler forms of actual bridge deck specimens and are a useful precursor to performing measurements over bridge decks. Figure 2 illustrates PERES at TFHRC.

Figure 2. PERES at Turner-Fairbank Highway Research Center.

PERES allows for flexibility in the way the system is setup. The sampling interval across the surface (spatial interval) and sampling interval vertically through the deck (temporal interval) may be varied. The antenna height, pulse repetition frequency, gains and filters may also all be set by the operator. The influence of these parameters is under study through a series of ongoing experiments.

2.3 Results of HERMES tests

A reconstructed image from measurements over an 'X' target made with metallic tape on the road surface is presented in Figure 3. The marked feature is visible in this plan view of the image. This figure demonstrates that the de-multiplexing and alignment of data from the different channels was achieved successfully. This is significant because existing GPR inspection systems for bridge decks use up to 4 channels yielding separate 2D profiles along the road. HERMES has transceivers spaced at 3 cm intervals across the roadway covering a total width of 1.9 m. This allows the data to be combined to a single file representing a 3D volume. Figure 3 also shows a cable running just beneath the surface of the road. The figure represents one plane of the available volume of data. Note that the imaging process gives higher amplitude signals a whiter appearance.

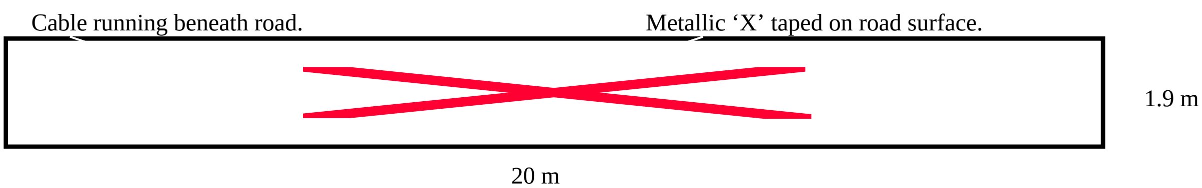

Figure 3. A plane through a reconstructed image of HERMES data taken over an 'X' marked out with metallic tape on the roadway.

Figure 4 illustrates a plan view of a slice through a reconstructed image from data collected during the tests at Truckee. The bridge over which the measurements were taken has a reinforced concrete deck with an asphalt overlay approximately 8 cm thick. The original data was collected using a sample spacing of 3 cm in the direction of travel. All 64 transceivers were used to generate a 3 cm sample interval across the road resulting in a regular square grid of data points. The HERMES trailer was towed at approximately 2 mph with the array at 7 cm from the road surface.

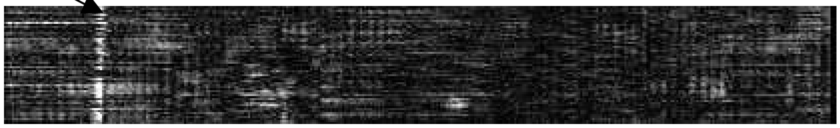

Figure 4. HERMES reconstruction of data taken at 2 mph with the array at 7 cm height.

The image of Figure 4 shows a strip of metallic tape that had been placed on the road surface. This plane is computed to be at a depth of 10 cm. The metallic tape appears at depths into the deck due to a combination of multiple reflections, between the road surface and antenna array, and ringing in the radar impulse. Such effects must be taken into account in the interpretation of the data. Throughout most of the image it is possible to discern the grid of reinforcing bars. At some locations, the grid is more apparent than others which may be due to variations in the thickness of asphalt, changes in signal attenuation due to variations in moisture and/or chloride content, or the presence of defects such as delaminations.

A HERMES survey was then conducted with the array raised to 12 cm and data collected as close to the speed of 2 mph as possible. The data is displayed in Figure 5.

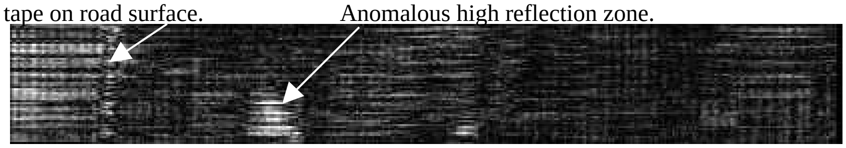

Figure 5. HERMES reconstruction of data taken at 2 mph with the array at 12 cm height.

The image of Figure 5 is the plane equivalent to that of Figure 4. In Figure 5 the same features are displayed though the rebar grid is not as clear as when the array was at 7 cm. This shows that it is preferable to set the array as close to the road surface as is possible for optimum feature definition. This is due to the spreading loss[6] which leads to reduced penetration into the deck as the antenna array is raised to greater heights. The marked anomalous zone indicates an area of relatively high reflection which may be caused by a defect such as a delamination. This property of the data may be correlated with a faint feature at the same location in Figure 4. This confirms that the phenomenon is produced by a physical characteristic of the deck and not system induced.

The travel speed was then increased to 20 mph. The same setup parameters discussed above were used in the third trial; 64 transceivers, 3 cm spacing and 12 cm height. The reconstructed image from this test is shown in Figure 6.

Figure 6. HERMES reconstruction of data taken at 20 mph with the array 12 cm height.

From Figure 6, the clarity of the image is degraded due to the higher speed. While the metallic tape is discernable its clarity is significantly reduced from earlier tests. The reinforcing grid is difficult to make out, but there remains slight indication of its layout. The influence of speed on data collection and processing will be evaluated further in subsequent trials.

2.4 Results of PERES tests

PERES was setup over a concrete slab which had been fabricated to include simulated defects. Reinforcing bars at a spacing of 30.5 cm (12 inches) had been included to form two grids at depths of 2.5 and 10 cm. Between one of the squares made by the rebars of the top grid a styrofoam block 2.5 cm thick had been inserted to simulate an air filled void. Figure 7 shows a reconstructed plane cut through the top rebar grid.

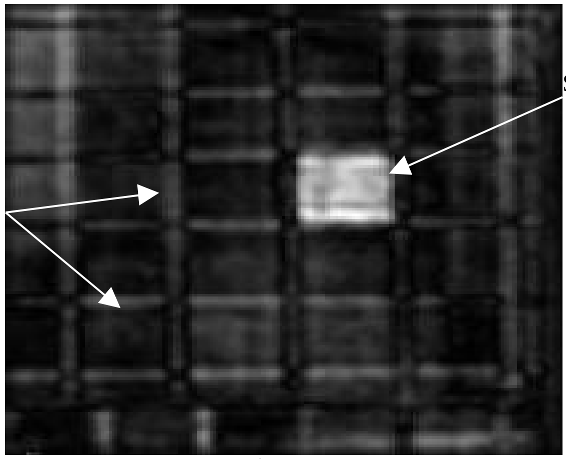

Figure 7. PERES reconstructed plane from data collected over a reinforced concrete slab with simulated void.

The styrofoam block is clearly indicated. The reflection from the styrofoam is greater in magnitude than that from the rebars, though the reflection coefficient magnitude is greater in the case of the steel rebars. (Assuming the dielectric constant of concrete equals 9, steel approaches ∞ and that of styrofoam is 2, the reflection coefficients between concrete and steel, and concrete and styrofoam are -1.0 and 0.36 respectively.) In this case it appears that the greater area and flat surface of the styrofoam returns more energy than the thinner, cylindrical surface of the rebars, even though the reflection coefficient magnitude is less. This indicates that the radar cross-section of the target[7] is important to consider in interpretation of the reconstructed images. The simulated void also appears more strongly than the rebars in the 3D rendered image of Figure 8.

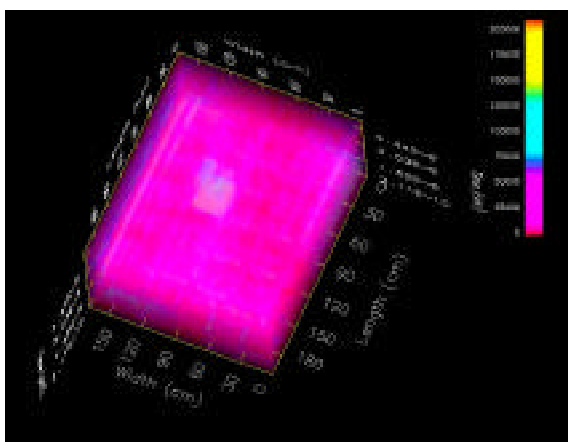

Figure 8. 3D rendered view of a volume of reconstructed PERES data over a concrete slab with simulated void.

The phenomenon of greater magnitude reflections has also been observed during field tests of PERES. Figure 9 shows data collected over a bridge deck where voiding was confirmed after coring in the area of high reflections. In the areas where the rebars show up, they are of a lower magnitude than the voided region.

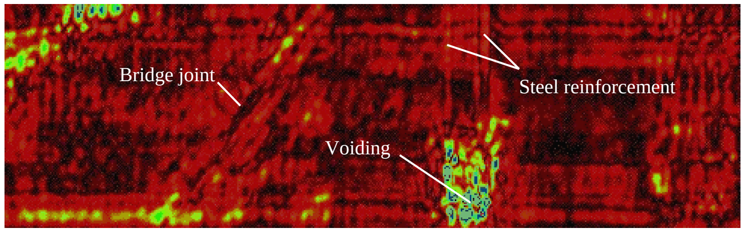

Figure 9. Plane of reconstructed PERES data through a voided bridge deck.

3. CONCLUSION

Results from preliminary testing with HERMES and PERES are presented. From tests with PERES, it is shown that air-coupled GPR systems have great potential as an effective deck assessment tool: Simulated and actual voids have been identified in processed data. The HERMES reconstructed data have shown, for the very first time, that 3D volumetric images through bridge decks are possible from a single pass with an array of closely spaced transceivers.

The primary goal for the two systems is to identify delaminations. An even more ambitious goal is to predict the areas where delaminations will form. This may be possible if it is shown that conditions for accelerated corrosion of the reinforcement are present. The identification of high levels of water and/or chlorides would indicate areas where delaminations are expected to form. At this stage in the evaluation of the systems destructive specimen removal and petrographic tests are required to corroborate interpretations of the radar data. A program of tests is planned to investigate more fully the systems' performance with change in setup parameters and type of defect. This will be achieved through testing at the NDE Validation Center at TFHRC and field trials over selected bridge decks.

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